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ScienceDirect

Procedia Engineering 5 (2010) 1180–1183

Procedia Engineering

www.elsevier.com/locate/procedia

Proc. Eurosensors XXIV, September 5-8, 2010, Linz, Austria

Fiber Bragg grating applied multi-functional sensor based on pulsed photoacoustic technique

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Abstract

A multi-functional sensor based on a pulsed photoacoustic (PA) technique is proposed. This sensor can simultaneously measure the chemical concentration, temperature, and flow speed of liquid using only one fiber Bragg grating. The concentration and flow speed of a sample liquid can be estimated by analyzing both the "shape" and the "amplitude" of a PA waveform observed with an oscilloscope. The DC voltage, which is biased on the PA signal, also depends only on the static temperature of the liquid. Our metal-free sensor head, which is basically maintenance free, is substantially noise proof without electro-magnetical shielding. We demonstrated that our proposed sensor functions as a multi-functional sensor within a concentration range from 1000 to 10,000 ppm with a Rhodamine 6G solution.

Keywords: multi-functional sensor; pulsed photoacoustic; fiber Bragg grating; optical fiber sensor

1. Introduction

The real-time monitoring of such chemical and physical values as concentration, temperature, and flow speed for raw liquids and wastewater is a required process control in chemical plants. The development of such an online measurement technique is desired. In the conventional way of satisfying this requirement, sensors must be individually prepared for separately measuring each parameter. Even though this method obviously has specific advantages, it is not necessarily an adequate sensor system from the viewpoint of cost performance and labor needed for maintenance. Nevertheless, sensing accuracy is exceeded. As one approach to solve these problems, a multi-function sensor system that allows us to simultaneously measure several parameters despite having only one sensor element have been investigated and developed[1]. This sensor system is particularly significant from the standpoint of actual use when a fiber optic technique can be applied.

In our earlier work, we proposed a fiber Bragg grating (FBG) applied pulsed photoacoustic (PA) detection technique for online monitoring of liquid concentration[2]. Our proposed sensor is substantially noise proof without electro-magnetical shielding, enabling actual use in industrial plants; additionally, our metal-free sensor head is not only small but also maintenance free because of non-metal erosion of electrode from acidity. Here, it is common knowledge that FBG can be applied as a sensor not only for directly measuring strain, deformation, and vibration but also for indirectly measuring temperature[3]. It was also demonstrated that the center wavelength

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1877-7058
doi:10.1016/j.proeng.2010.09.322

of FBG's pass-band is transited, even when the temperature change, which depends on the power of the laser beam from the fiber core into FBG, is induced by the photothermal effect[4]. This paper proposes a pulsed PA technique applied multi-functional sensor that can simultaneously measure chemical concentration, temperature, and the flow speed of liquid using only one FBG. First, we describe the sensing principle of our proposed multi-functional sensor system and then demonstrate the experimental results. Finally, its sensing capability is discussed.

2. Sensing principle

2.1. Static temperature sensing

The temperature of the sample liquid can be simply measured by compensating the DC voltage measured with a DC voltmeter (Fig. 1). This technique, which has been already practically used, is widely known as a commercially available FBG temperature sensor[3].

2.2. Pulsed PA spectroscopy

Pulsed PA spectroscopy is based on the absorption of the short laser pulse inside the condensed matter. Due to the thermal expansion of the medium, generated pressure waves can be detected by FBG fiber[5]. Here, the energy absorbed inside an irradiated medium with optical absorption coefficient α of the specimen is given by:

$$Q_{(l)}=Q_0[1-\exp(-\alpha l)], \quad (1)$$

where Q_0 is the laser energy and l is the distance from the specimen surface along the laser beam: i.e., "gap" d, shown in Fig. 1. Next, in the case of $al \ll 1$, Eq. (1) can be approximated by a primary linear function, and amplitude P of the PA signal can be introduced by:

$$P \propto (\beta c^2/C_p)Q_0\alpha, \quad (2)$$

where β is the thermal expansion coefficient, c is the sound velocity, and C_p is the heat capacity.

Next, depending on the optical absorbance of the medium, different PA waveforms are obtained. For weakly absorbing samples, a cylindrical wave, which propagates perpendicularly to the laser beam, is formed because the volume irradiated by a collimated beam is approximately cylindrical. On the other hand, when optical absorbance increases (i.e., in the case of highly absorbing and opaque samples), spherical waves are generated because the optical penetration depth and the irradiated volume decrease. Accordingly, even if the absorption coefficient varies over several orders of magnitude, based on Eq. (2), linearity between the PA signal amplitude and the sample concentration can be obtained even though different waveforms are generated. From these relations, the linearity of detection must be obtained with a wide range of acoustic intensity as the condition for designing the sensing element, whose details are described in ref. [2].

Here, the "shape" of a waveform of a pulsed PA signal is affected only by the change in the concentration of the liquid, not by a change in its flow speed. The reason for this is believed to be that the waveform of the detected PA signal becomes too "sharp" as the optical penetration depth (which depends on the liquid concentration) is shallower, but an optical penetration depth is not essentially affected by the fluid's flow speed. On the other hand, the amplitude (or peak-to-peak value) of the waveform is affected by both the liquid's concentration and its flow speed. In other words, the amplitude of the wave form is suppressed as the flow speed becomes faster when the liquid concentration makes no difference because of smooth thermal radiation. Consequently, we believe that the liquid's concentration, which depends on the optical penetration depth, and its flow speed can be estimated by analyzing both the shape and amplitude of a pulsed PA waveform with an oscilloscope.

3. Sensing system

Figure 1 shows a block diagram of the sensing system. A Q-switched frequency doubled Nd:YAG laser (λ=532 nm, Continuum Minilight) with a repetition rate of 10 Hz was used for the PA excitation beam source. The pulsed beam was focused using a plano-convex lens (whose focal length is 150 mm), guided into the 0.6-mm-diamter step index (SI) fiber, and finally fed to the sensor head. The laser energy can be adjusted with an optical attenuator installed in the laser equipment. The broad beam from the amplified spontaneous emission (ASE) light source with a wavelength of 1530 to 1570 nm was fed to the FBG sensor through the optical circulator, and the beam reflected

with the FBG was returned to the circulator and fed to an InGaAs pin photo diode (PD) for detecting the optical amplitude through the optical band-pass filter (BPF). Here, the full-width at half-maximum (FWHM) of both FBG and BPF as well as the difference between the wavelength centers of FBG and BPF are significant parameters for determining the sensing characteristics. In this paper, we set the FWHMs of FBG and BPF to 0.5 and 1 nm, respectively, and set the difference of the center wave length between FBG and BPF to 1 nm, enabling the optimization of relations among linearity, sensitivity, stability, and portability. Furthermore, the optimum design of these parameters was described in ref. [2].

Here, in our case, since it is common knowledge that the temperature rises no more than 10^{-2} K by photothermal effects, we believed that the above DC voltage only depends on the static temperature of the sample liquid. Furthermore, the DC voltmeter (shown in Fig. 1) does not operate at the short pulse with approximately 100 ns of PA excitation beam.

Figure 1 also illustrates the operation of the flow cell, which is made of polycarbonate resin because of easy preparation, whose flow guide for fluid was 2.0 mm diameter (i.e., gap d=2.0 mm). Furthermore, in practice, the cell should be made of quartz to avoid metal erosion from acidity and contamination from resin. The flow speed is precisely controlled by the fixed quantity flow pump, and the fluid is fed to the measurement unit with a closed cycle circulating system. The signal detected by PD was recorded by a digital storage oscilloscope (Agilent Infiniium 54831B) with a time-resolved mode after the signal was amplified. The PA signal was averaged 100 times with an oscilloscope because of the enhancement of the signal-to-noise ratio.

4. Sensing results and discussions

The concentration of dye (Rhodamine 6G, which has powerful optical absorption at 532 nm) dissolved in distilled water was used to estimate the capability of our technique. Laser energy with fiber-out was adjusted to approximately 2 mJ to avoid breakdown of the dye particle. Fig. 2 shows the flow speed dependence of the FWHM of the waveform observed with an oscilloscope at room temperature, as the function of the concentration of dye solution. Fig. 3 also shows the flow speed dependence of the waveform amplitude. As seen in these figures, the FWHM of the waveform, which contributes to the "shape" of waveform, becomes small, as the concentration increases. This is because the optical penetration depth becomes shallow, thereby reducing the acoustic generation region. But the FWHM of the waveform did not depend on the flow speed. On the other hand, the signal amplitude of the waveform becomes high, as the concentration increases. This result is proper; it is remarkable that the amplitude is reduced, as the flow speed increases. The reason is believed to be as follows.

Due to the thermal expansion of the medium, generated pressure waves can be detected by the FBG fiber. Here, the pressure intensity of the wave is not reduced due to the fluid flow, but slight heat induced with a photothermal effect is susceptible to diffusion, thereby suppressing the rise in temperature. This resembles the working principle of a commercially available electrical hot-wire flow sensor. Note that it is widely known that FBG sensors function normally as high-precision and high-resolution temperature sensors. Consequently, we confirmed that FBG applied our PA sensor functions as a multi-functional sensor.

Next, we arranged the experimental data shown in Figs. 2 and 3 to discuss the relation and tendency among parameters. Fig. 4 shows the following concentrations of fluid dependence: a) FWHM and b) the gradient of the lines shown in Fig. 3. As seen in this figure, next a) and b) are found. a) The FWHM of the waveform becomes low as the liquid concentration thickens. Nevertheless, FWHM was saturated when the concentration was below 3000 ppm, probably because the optical penetration depth becomes deeper than gap d shown in Fig. 1 (i.e., distance between the FBG sensors and PA generating point), thereby limiting the thermal expansion volume of the medium. b) The gradient of the lines, which mean the influence of the temperature sensitivity, become high as the liquid concentration thickens. This demonstrates that a temperature falling ratio against the flow speed becomes high for high concentration. Furthermore, a singular datum was exhibited when the concentration was 6000 ppm, and the reason is under consideration.

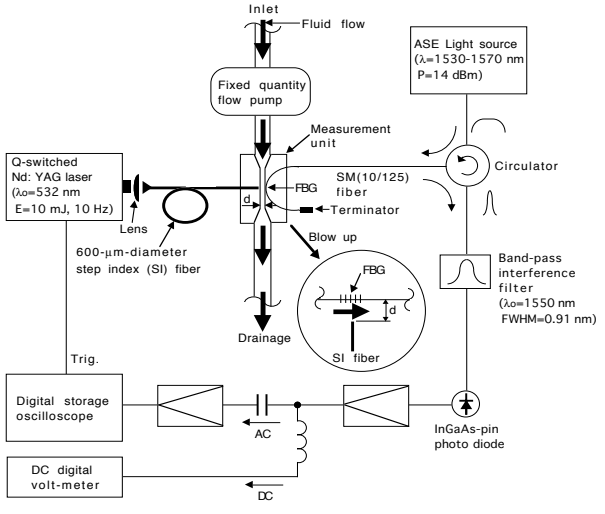

Fig. 1. Block diagram of sensing system.

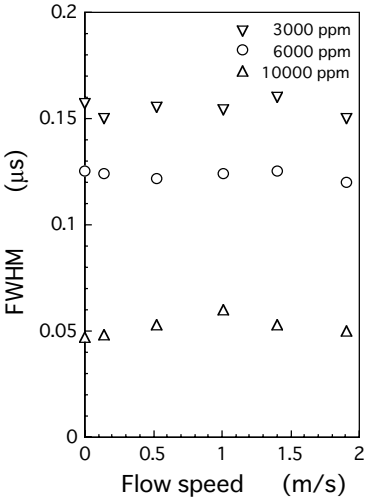

Fig. 2. Flow speed dependence of FWHM of waveform.

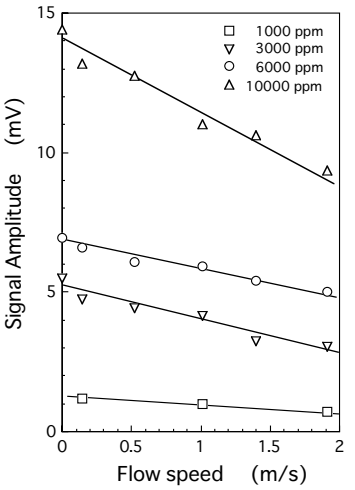

Fig. 3. Flow speed dependence of amplitude of waveform.

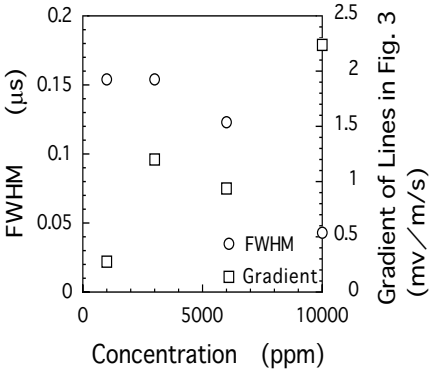

Fig. 4. Concentration dependence : a) FWHM and b) gradient of lines shown in Fig. 3.

5. Summary

This paper proposed a pulsed PA technique that applies a multi-functional sensor that can simultaneously measure the chemical concentration, temperature, and flow speed of liquid using only one fiber Bragg grating (FBG). The concentration and flow speed of a sample liquid was estimating by analyzing both the FWHM and the amplitude of a pulsed PA waveform observed with an oscilloscope. The concentration of Rhodamine 6G dissolved in distilled water was used to estimate the capability of our technique. With a concentration range from 1000 to 10,000 ppm, we confirmed that the FWHM of the waveform of a pulsed PA signal was only affected by the change in the liquid concentration, not by a change in its flow speed. On the other hand, the amplitude of the waveform was affected by both the concentration and flow speed. We also verified that our technique is suitable for a high-concentration and opaque liquid without the influence of scattering particles included in the fluid. The DC voltage, which is biased on the PA signal, also only depends on the static temperature of the liquid. We believe that our proposed pulsed PA sensor functions as a multi-functional sensor and expect it to be a useful online sensor technique in the chemical industry.

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